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Original Research Articles

Analysis of the Impact of Aquaculture and Agriculture on Food Security under the Pressure of Pollution

Mohd Alsaleh[1a], A.S. Abdul-Rahim[2,3]

[1] College of Economics and Management, Shanghai Ocean University, Shanghai, China, [2] School of Business and Economics, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, [3] Institute of Tropical Agriculture & Food Security (ITAFoS), Universiti Putra Malaysia, Serdang, Malaysia

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Both aquaculture and agriculture are essential for food security in Europe, but they face different challenges and opportunities. A sustainable and balanced approach that considers both sectors is needed to ensure that Europe can meet its food needs while protecting the environment and promoting economic growth. This research is aimed at studying the economic analyses of the effect of aquaculture versus agriculture production on future food security in the EU27 region from the era between 1990 and 2023. Resolve challenges of endogeneity, employing econometric estimators such as the robust least squares (RLS), two-stage least squares (2SLS), and ordinary least squares (OLS), producing crucial insights. The analysis reveals that in the EU27 region, agricultural production has a higher impact than aquaculture production on influencing food security. Moreover, in the EU13 developing countries, aquaculture production has a higher impact on food security than in the EU14 developing countries. On the other hand, in the EU14 developed countries, agriculture production plays a significant role in food security in comparison with the EU13 developing countries. From another perspective, economic growth, governance, and fossil fuel consumption variables play a significant role in food security in the EU13 members compared with the EU14 members. Based on the study's findings, policymakers in the EU27 region are advised to provide policies targeted at advancing the aquaculture sector top priority to achieve food security in the future, especially in EU14 developed countries. Additionally, this study suggests that decision-makers in the EU13 members need to improve the efficiency of agriculture production to meet the food security targets.

INTRODUCTION

EMPIRICAL BACKGROUND

The European Parliament has passed the Natural Restoration Law. It aims to restore 20% of the EU's land and marine ecosystems by 2030 and all ecosystems in need of restoration by 2050. This law is expected to reduce the risk of food security by reversing the decline of pollinating insect populations, increasing carbon storage in forest and farmland soils, and restoring the free flow of rivers.[1-4] The European Union (EU27) faces the complex challenge of ensuring food security amidst a changing climate, increasing global demand, and the need for sustainable practices. This research paper examines the crucial roles of aquaculture and agriculture in bolstering food security within the EU, analyzing their current state, identifying key challenges, and exploring potential solutions for a resilient and sustainable food system.[4] Food security, defined as access to safe, nutritious, and sufficient food for all, is a fundamental human right. The EU, with its diverse agricultural landscape and growing aquaculture sector, has the potential to play a significant role in addressing global food security challenges. This paper will delve into the present status of fish farming and agriculture in the EU, analyzing their contributions to food security and identifying key challenges and opportunities.[4]

The growth potential of fish farming in the EU for food security is manifested in several aspects, as follows: (1) Increased yield in central and eastern Europe, there are 250,000 hectares of fish ponds in Central and Eastern Europe.[5,6] At present, the carp production is about 120,000 tons annually with a low yield of ⩽0.5 tons per hectare. Through ecological aquaculture, the yield can be increased to over 1 ton per hectare, potentially increasing the annual output to about 250,000 tons. (2) Growth in marine aquaculture, for marine finfish production in the EU, salmon

a Corresponding author, Mohd Alsaleha, Email: moe_saleh222@hotmail.com

and trout cover 53% of the total production, and sea bass and sea bream cover 38% (Wang et al.[5] and Jolly et al.[6]). From 2000 to 2016, salmon and trout production increased by 23%, and sea bass and sea bream by 62%. With continuous technological innovation and improved breeding techniques, there is still potential for growth in marine aquaculture. (3) Promising seaweed aquaculture, seaweed aquaculture in the EU is small but growing.[5-7] The Aquaculture Advisory Council has called for the development of a legal framework, site selection protocols, and farming technologies to promote its growth, indicating great potential for future expansion.

As a rising star, the aquaculture sector, or fish farming, is experiencing rapid growth in the EU. Its contributions to food security include: (1) Diversification of protein sources, aquaculture provides a valuable source of protein, complementing traditional livestock and plant-based diets (Alsaleh, 2024; Alsaleh et al., 2024c; Uzunova et al.[8]). (2) Reduced reliance on wild-caught fish, by reducing pressure on overfished wild stocks, aquaculture promotes sustainable fishing practices.[9,10] (3) Economic growth and job creation, the aquaculture sector generates employment opportunities and contributes to the improvement of the socioeconomic livelihood of fishing and farming communities.[8,11] However, the rising star of mariculture is not without challenges such as: (1) Environmental impacts, concerns exist for pollution as a result of aquaculture activities, as well as destruction of habitat, and the spread of diseases. (2) sustainability concerns, ensuring the sustainability of feed sources, minimizing antibiotic use, and reducing the carbon footprint of aquaculture are crucial challenges. (3) Market access and consumer acceptance, expanding market access for EU aquaculture products, and addressing consumer concerns about food safety and quality are essential.[8]

On the other hand, as per earlier research by Bermejo et al.[12] and Naylor et al.[13] a backbone of food security, agriculture remains a cornerstone of the EU27's food system, providing a diverse range of food products and supporting rural communities. Its contributions to food security include: (1) production of food and supply, agriculture provides a stable supply of essential food commodities, including grains, fruits, vegetables, and meat. (2) Rural development and agriculture support rural economies and livelihoods, contributing to social and economic stability.[12,13] (3) Biodiversity conservation and sustainable agricultural practices can lead to the improvement of aquatic habitat and ecological preservation. In the same manner, this backbone of food security is not without challenges such as; (1) Climate change, climate change poses significant threats to agriculture, including extreme weather events, changing precipitation patterns, and increased pest and disease pressure (2) Sustainability concerns, addressing issues such as soil erosion, water scarcity, and the overuse of pesticides and fertilizers is crucial for sustainable agriculture.[14] (3) Market volatility, fluctuations in global commodity prices, and market demand can impact the profitability and stability of agricultural production.[14]

To fill up the gap of previous research, the main questions of this research are as follows: (1) Can the aquaculture sector play a main role in food security in the EU27 region by 20230? (2) What is the status of the aquaculture sector versus the agriculture sector toward food security in the EU27? (3) How is the economic structure of the EU13 members in comparison with the EU14 member's responses in the aquaculture sector and agriculture sector towards food security? This study undertakes an in-depth exploration of food security within the European Union (EU) from 1990 to 2023, focusing specifically on the burgeoning aquaculture sector versus the agriculture sector. The main aims of this research are: (1) to economically analyze the level of contribution of the aquaculture sector in the EU13 members versus the EU14 members to achieve the food security targets by 2030. (2) to explore the level of contribution of fish farming versus agriculture in the 27 European Union members to achieve the food security objectives by 2030. (3) to economically analyze the level of contribution of the agriculture sector in the EU13 members in comparison with the EU14 ones to achieve the food security targets by 2030.

Generally, this research novelty contribution can be summarised as (1) Explores sustainable food security alternatives to reduce reliance on traditional fisheries resources. (2) Explores sustainable food security alternatives to reduce reliance on traditional agriculture. (3) Enhancing food security in the EU while reducing the effect on the ecology of the land and safeguarding the future sustainability of the sector. (4) The applied 2SLS estimator is primarily used to address the issue of endogeneity in regression models that occurs when there's a correlation between an independent variable and the error term, leading to biased and inconsistent estimates. (5) The applied economic theory provides a framework for understanding food security issues, but it's not the only perspective, therefore this research included social, political, and environmental factors that also play crucial roles. (6) This research explains the economic dimensions of food security to develop more effective strategies to ensure that everyone has access to safe, nutritious, and affordable food in the EU27 region.

This research offers several key novelties and contributions compared to other traditional research within the context of EU food security as follows: (1) The approach of the two-stage least squares (2SLS) estimation of the aquaculture sector, examines its level of contribution to food security targets across the EU27 region. (2) Utilizing the 2SLS approach, it conducts a comparative analysis of aquaculture sector effects on food security aims in the EU13 in comparison with the EU14 ones. (3) Employing the 2SLS estimator, this research probes into the effects of both the fish farming industry versus the agriculture sector on food security within EU13 members versus EU14 members. The following *Theoretical background* sub-section reviews research on how individual elements related to the macroeconomics of aquaculture contribute to food security.

THEORETICAL BACKGROUND

Since maricultural food systems preserve bio-diversity and environmental services while offering sustainable protein sources, they are crucial to ensuring the world's supply of food. The significance of aquaculture in addressing food and nutrition security was acknowledged by earlier research that examined the role of aquaculture in the food insecurity agenda in emerging economies.[15,16] Furthermore, another two papers investigated the challenges posed by the declining efficiency of the fishing and aquaculture sectors in light of climate change, highlighting the implications for endangered households and the sustained security of food.[17,18] Similar to this, other papers examined how small-scale fishing in Africa could enhance lives and food security. They emphasized the importance of small-scale fishing enterprises in providing jobs and food, but they also emphasized threats to their sustainability and profitability, such as industrialization and climate change.[19-22]

Rahman et al.[23] found a positive link between measures of household food security and fisher's responses to climate change, indicating that global warming resilience has an impact on family food security in Indonesia. Additionally, Syddall et al.[24] looked at the social-ecological systems supporting the tuna fishery in the Solomon Islands and assessed their resilience and vulnerability, emphasizing the need to encourage cooperation and coordination within frameworks related to aquaculture and governance. The intricate connections between aquaculture, fisheries, food security, and climate change are shown by this research together, highlighting how urgent it is to advance sustainable methods and strengthen resilience within these industries. In a similar vein, Setsoafia et al.[25] investigated how environmentally friendly farming procedures affected farm revenue and nutritional security in Africa. They recommended strong agricultural governance and management to improve sustainable food security and suggested several regional collaborative frameworks, national aquaculture and fishing programs, and local cooperative and coordination mechanisms to increase the resilience of fisheries and aquaculture systems to climate change.

In developing countries, a robust agricultural sector serves as the cornerstone of food security while also contributing significantly to national income. Using agent-based analyses, earlier papers thoroughly examined the potential influence of agriculture climate change resilience toward food sufficiency.[26,27] They assert that this approach has the potential to improve rural communities' quality of life, especially for farming households that have access to integrated food markets, article social networks, and financial resources. The roles of land-use changes, farming productivity, climate dynamics, farmer incentives, cities and outskirts of cities the farming industry, and the suitability of soil in promoting environmentally friendly agriculture have also been clarified by earlier papers,[28,29] who have carefully examined a variety of aspects of agricultural research. Previous studies conducted in India shed light on the vulnerability of marginalized and minor agricultural families to food insecurity due to climate-induced fluctuations in agricultural output and food prices,[30,31] emphasizing the imperative of understanding climate variability's effects on rural agricultural productivity and food security.

Investigating the interplay between energy and food security, Hunter,[32] Luqman, and Al-Ansari[33] accentuated the indispensable role of renewable energy technologies in bolstering the long-term resilience of food systems. Similarly, Granit et al. (2022) adopted the Energy-Water-Food sufficiency Nexus paradigm to analyze the impacts of energy innovations on societies in Colombia, highlighting the contribution of renewable energy in enhancing access to food and water towards achieving sustainable development goals. On the other hand, another paper searched the connection among green power generation and nutrition sovereignty in the United States,[34] warning that policies that support renewable energy could unintentionally impact food security's supply and affordability. The equilibrium of the environment within the water-energy-food security relationship across the continent of Africa was examined in other studies that argued for the adoption of the global hectare approach as a relevant tool for assessing the ecological viability of water, energy, and food output.[35-38]

To ensure a sustainable food system, Rasul et al.[39] advocated for the implementation of integrated, ecologically friendly food-energy systems in South Asia, considering external influences on sustainable food systems. To achieve global food security and promote economic growth, two previous papers examined nutrition stability and economic development across some sectors, highlighting the need for a balanced approach that includes agriculture, delivery, and waste reduction.[40,41]

Likewise, earlier papers explored the nexus among nutrition sufficiency and economic outgrowth across various sectors, emphasizing the necessity of a balanced strategy encompassing nutrition output, transportation, and food loss reduction to achieve global food security and stimulate economic growth. The relationship between agricultural productivity and sustainable economic growth in Asia was examined by Yaqoob et al.,[42] who emphasized the vital role that technological innovation would play in satisfying future food needs and furthering the sustainable development cycle. Similarly, Ajayi et al.[43] stressed how important it is for rural development plans to include renewable energy for power production to maintain economic growth, especially in the agricultural and food security sectors in Africa. Research on social, economic, agricultural, and climatic aspects of food security was carried out in China by Lv et al.[44] and Qi et al.,[45] who emphasized the critical role that economic development plays in attaining continuous food supply and development.

The European Union (EU) promotes the sustainable management of fish and seafood resources, the outlawing of unreported, unregulated, and illegal fishing methods, and the strengthening of marine cooperation and ocean governance to promote a worldwide transition towards a sustainable agri-food system. Adelle and Dekeyser et al. (2022), Collins,[46] Jones et al.,[47] and Leeuwis et al.[48] all looked at how governance of the fisheries and aquaculture industries affected food security and development. Accordingly, the circle of sufficient food and nutrition efficiency may be strengthened by efficient governance in these areas. Similar to this, Iitembu et al.,[49] Ahwireng,[50] Anser et al,[51] and Haysom[52] looked at how the fisheries and aquaculture industries are run in Africa and suggested that, like agriculture, these industries need a legal framework that guarantees tenure security and determinable property rights, pointing out that this important criterion is only partly met by the African ocean governance framework, emphasizing the need for more governance mechanism improvements.

Lack of comprehensive and region-specific analysis, while studies often examine the individual contributions of aquaculture and agriculture to food security, there's a dearth of research specifically analyzing their interconnectedness within the EU context. This gap hinders a holistic understanding of how these sectors influence each other and their combined impact on food security across different European regions. (2) Synergies and trade-offs, aquaculture and agriculture are intertwined. For example, aquaculture can utilize agricultural by-products as feed, while agriculture can benefit from aquaculture waste as fertilizer. Conversely, competition for resources (water, land) and potential environmental impacts (pollution) can create trade-offs. (3) Regional disparities, the EU exhibits significant regional variations in agricultural production, aquaculture development, and food security challenges. A region-specific analysis would reveal how these interconnections play out differently across the continent. (4) policy implications: Considering the complex connections that exist between aquaculture and agriculture is essential to creating policies that improve food security while reducing possible hazards. This includes optimizing resource allocation, promoting sustainable practices, and fostering collaboration between these sectors.

In the past, several scholars have applied methodologies, for example MMQR, ARDL approaches, and POLS regressor to examine the indicators that affect food security. However, since fixed-effect estimators may have inherent biases, these approaches may provide less accurate results. Furthermore, the endogeneity issue about the aquaculture sector's influence on food security was often disregarded in previous studies. To overcome these constraints, this research uses multi-year data covering the years 1990 to 2023 to examine the link between the aquaculture sector versus agriculture toward food security indices across different economic development structures in the EU27 region. An extensive analysis of this linkage is made possible by extending the sample to include the EU13 members and the EU14 members of the European Union. Likewise, the study uses modeling frameworks like two-stage least squares (2SLS) and robust least squares (RLS) to solve the endogeneity problem.

By addressing this research gap, we can gain a more nuanced understanding of how aquaculture and agriculture can work together to enhance food security in the EU while ensuring sustainability and minimizing negative impacts.

METHODOLOGY AND DATASET

THEORETICAL FRAMEWORK

The institutional economic theory provides valuable frameworks for understanding the complex challenges of food security. Policymakers can foster the sustainable growth of the EU agriculture and aquaculture sectors and thereby contribute to nutrition security and economic expansion by comprehending the institutional framework and implementing suitable economic principles (Alsaleh, 2024). The EU's aquaculture sector and agriculture sector play a crucial role in food security, and institutional economic theory provides a framework for understanding the challenges and opportunities within this context. Key Institutional Economic Concepts Relevant to EU Food security[11]: (1) Property rights, clearly defined and enforced property rights over aquaculture resources (e.g., water bodies, fish stocks) are essential for sustainable management and investment. (2) Transaction costs, the costs associated with market exchanges, such as information asymmetry, contract enforcement, and market power, can hinder the efficiency of aquaculture value chains. (3) Governance structures, effective governance mechanisms, including regulations, standards, and market-based instruments, are needed to address externalities, ensure food safety, and promote sustainable practices.[5,53] (4) Social capital, trust, cooperation, and networks among stakeholders (e.g., farmers, processors, consumers) can facilitate knowledge sharing, collective action, and innovation in the aquaculture sector.[53]

The analysis revealed variations in the model response pattern across different samples, impacting the classification of institutional economic theory. Nonetheless, all measures' contemporaneous validity has been verified.[54] This underscores the necessity for a reassessment of the food security economic model. Consequently, recent research endeavors by Wang et al.[7] and Wang and Alsaleh[54] have culminated in the development of a comprehensive model aimed at addressing these methodological challenges and enhancing the accuracy of food security assessment within the EU.

$$FS_{it} = f\,(AQ_{it}, AG_{it}, FF_{it}, GDP_{it}, GVR_{it})$$

ECONOMETRIC METHODOLOGY

The purpose of this research project was to compare the economic contributions of the aquaculture and agriculture sectors to food security in the European Union (EU27 member nations) between 1990 and 2023. The study used a two-stage least squares (2SLS) approach to assess how different food sources affect food security to meet the 2030 targets, using the secondary dataset from different sources as shown in Table 1 . Additionally, the research divided the region's nations into two groups—European Union Developed Countries (EU14) and European Union Developing Countries (EU13)—according to the structure of their economies and degree of advancement to make the comparison among them simpler. Thus, the following is how this study describes the study's model:

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \varepsilon_{it} \quad (1)$$

This study extends and modifies the model established by incorporating various possible food security determinants, denoted as X vectors, and representing the aquaculture sector as Y, with Ɛ representing the unobserved variable. Additionally, nation and period are indicated by the subscripts i and t, accordingly. Based on the findings of Alsaleh et al.[9, 10] and Alsaleh and Wang,[11] the present research improves and streamlines the current model in the ways listed below.

$$FS_{it} = \beta_0 + \beta_1 AQ_{it} + \beta_2 AG_{it} + \beta_3 GVR_{it} + \beta_4 GDP_{it} + \beta_5 FF_{it} + \varepsilon_{it} \quad (2)$$

The appropriate evaluation of food production security levels in the equation necessitates the availability of reliable data, with food and nutrition production levels estimated using average values. According to the Food and Agriculture Organization, the letter (FS) stands for the food supply and production index (FAO, 2023). (AQ) refers to the farming of aquatic organisms including fish, mollusks, crustaceans, and aquatic plants. Aquaculture production specifically refers to output from aquaculture activities, which are designated for final harvest for consumption. Agricultural land, often known as the "agricultural production index," or "AG," is the percentage of the land mass that is cultivable, supported by persistent pastures and crops. According to the World Bank (2023), arable land comprises land that is briefly unused, land under market or kitchen gardens, land under temporary meadows for cutting or grazing land, and fields under seasonal crops (double-cropped areas are included once).

Among the independent variables, (GVR) reflects the governance index, captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. The European Commission's database provides economic growth indexed by GDP, which is computed in constant US dollars. (FF) represents energy consumption in metric tons of oil equivalent and serves as a proxy for fossil fuels, derived from a European Commission database.

The World Bank's Indicators database (WDI), the European Commission's database, and the official website for European Statistics (Europa) are the sources of annual data for the participating nations. These sources collectively provide the necessary data to achieve the study's objectives. Table 1 presents the data, including transformations, sources, and measurement units. Every metric used in the present research is transformed into logarithmic form, as explained in Table 1. Time and nation are indicated by the subscripts i and t, accordingly, whereas the error term is represented by Ɛ, the intercept by β0, and the coefficients by β1, β2, β3, β4, and β5.

The methodology of this study seeks to construct a cross-sectional model of food security, incorporating a comprehensive range of variables that influence both the aquaculture sector and the agriculture sector. Based on the work of Wang and Alsaleh,[54] Wang et al.,[7] and Wang et al.,[5, 53] the econometric model of food security is designed to account for varying degrees of economic structure.

$$Y_{it} = \beta_0 + \beta_1 Y_{it-1} + \beta_2 X_{it} + \mu_{it} + \varepsilon_{it} \quad (3)$$

Where, i = 1, ...N, t = 1,...T.

Y_{it} is regressed on the exogenous independent variables (X_{it}) and the lagged dependent variable. The error term is composed of the individual-specific effect (μ_{it}) and the white noise error term (ε_{it}). This research uses an econometric model to investigate the connection between elements in the fish farming industry versus the agriculture sector and food security in the EU27 region. The authors use a cross sectional analysis technique to analyze data from sample members to successfully assess the study's hypothesis. Cross sectional analyses are particularly well-suited for this type of research since they consider each cross-sectional and time-series adjustment to the data. This method allows the researchers to account for potential time- and nation-specific changes while capturing cross-national variability.

H_1: Aquaculture output is one of the fastest-growing for food security and public health

H_2: Boosting agricultural output can ensure enough food security and public health.

For standard analysis, the researchers employ Ordinary Least Squares (OLS) regression with year- and country-fixed effects. This approach helps to minimize potential biases and generates more accurate forecasts of how the growth of the agricultural and aquaculture/agriculture sectors might impact food security by controlling for time-specific impacts and error term variations between nations.

As a result, the research uses the panel data econometric model in conjunction with pertinent literature to perform empirical analysis to investigate the effect of fish farming and agricultural industry growth on food security. To reliably estimate endogenous models, the research also employs extra analysis using Robust Least Squares (RLS) approaches. Furthermore, the Two-Stage Least Squares (2SLS) estimator is employed to resolve any endogeneity issues and show a causal correlation among the outgrowth of the fish farming sector and food security. To address endogeneity issues, this study employs the popular and effective econometric techniques of 2SLS and RLS methods, as well as instrumental variables that have been utilized in related studies such as Greene,[55] Kennedy,[56] Cooray,[57] and Khan et al.[58,59]

FINDINGS AND OUTCOMES

OUTCOME OF ECONOMETRIC ESTIMATION

To minimize variance and produce accurate estimators, it is crucial to use natural logarithms for all variables, as shown in Table 2, which also includes summary statistics and descriptive statistics. This log transformation is essential for enhancing the effectiveness of estimators by minimizing variability among the variables. The findings of the linkage analysis are presented in Table 3.

Notably, the results highlight little relationship between the explanatory components, indicating the lack of multicollinearity problems. Multicollinearity is therefore not expected throughout variable evaluation across the same model. Moreover, Table 3 illustrates the correlation matrix

Table 1. Summary of Variables.

Variable	Abbreviated	Data Source	Measurement Unit
Food Security	FS	WDI	(2004-2006 = 100)
Aquaculture Production	AQ	WDI	metric tons
Agriculture Production	AG	WDI	Agricultural land (% of land area)
Governance	GVR	Eurostat	% of confidence in governance
Fossil Fuel	F	Eurostat	metric tons of oil equivalent
Economic Growth	GDP	Eurostat	Gross domestic product (constant $)

Table 2. Results of Descriptive-Statistics

Factors	Obs.	Mean	Std. Dev.	Min	Max
FS	918	2.001	0.044	1.848	2.227
AQ	918	4.123	0.858	1.643	5.638
AG	918	1.584	0.255	0.848	1.867
GDP	918	4.377	0.395	3.129	5.253
FF	918	2.753	0.761	0.011	4.600
GVR	918	1.867	0.070	1.482	1.979

Source: Author's calculation

Table 3. Panel Data Matrix Analysis

Factors	FS	AQ	AG	GDP	FF	GVR
FS	1.000					
AQ	0.065	1.000				
FF	0.020	0.381	1.000			
GDP	0.073	0.126	0.127	1.000	1.000	
IQ	0.032	0.203	0.162	0.645	0.016	1000

between aquaculture parameters and food security, revealing a positive and statistically significant correlation coefficient of 0.065. This finding suggests that greater involvement in agriculture production and aquaculture production coincides with food security in European countries, as evidenced by the positive values. Furthermore, a favorable association is observed between agriculture and aquaculture development and all metrics, with the correlation being particularly strong for the sustainability of food security.

Before estimating the parameters, standard preliminary tests are conducted to ascertain the time series characteristics of the variables. This study prioritizes investigating cross-sectional dependence (CD) within the panel due to the potential for erroneous coefficient estimations if such dependence is overlooked. Ignoring cross-sectional dependency might reduce the effectiveness advantages typically connected with panel data analysis and jeopardize the accuracy of coefficient estimates, which frequently result from unexplained common factors.[60] Subsequently, addressing this issue is imperative to ensure the reliability of coefficient estimates. To assess cross-sectional dependence within the panel, the Pesaran[61] CD test is employed. The findings, as presented in Table 4, indicate substantial correlations among all quantitative components across countries. Incorporating unit root and cointegration tests, alongside methodologies resilient to the influence of cross-sectional dependence, is crucial in panel estimation procedures to mitigate the risk of size distortions. To objectively assess the combining qualities of the variables, the authors use panel non-stationarity tests as suggested by Breitung,[62] Im-Pesaran-Shin (IPS),[63] and Breitung and Das[64] (see Table 5). The Breitung[62] and Breitung and Das[64] tests maintain the assumption of a single autoregressive parameter for each panel member, whereas the Im-Pesaran-Shin (IPS)[63] test reduces this premise. Table 5 illustrates that the Breitung[62] panel unit root test exhibits superior power compared to similar unit root tests, particularly for relatively large panel datasets akin to the one utilized in this study. Breitung and Das[64] introduced the panel unit root test as an alternative to methods considering cross-sectional dependence. The authors utilize these three tests to evaluate the extent to which cross-sectional dependence influences panel unit root testing. Notably, Table 5 demonstrates that all variables exhibit non-stationarity at levels but stationarity at first differences for each unit root test specification,

Table 4. Cross-Sectional Dependence Results

Factors	FS	AQ	AG	GDP	FF	GVR
Test	(3.12)***	(5.95)***	(45.56)***	(83.55)***	(65.35)***	(31.30)***

Remark: *** refer importance at the 1%, scale.

Table 5. The interpretation of panel unit root tests

Factors	Diff.		1^{S} Diff.	
	LLC	IPS	LLC	IPS
FS	0.609***	5.000	37.388***	29.637***
AQ	3.884***	10.385	15.406***	28.510***
AG	7.882***	12.021***	18.287***	26.210***
GDP	21.53***	15.59***	60.12***	61.75***
FF	8.696***	5.224***	14.380***	16.814***
GVR	10.911**	18.011***	13.687***	21.324***

Remark: *** refer importance at the 1%, scale.

indicating an integrated order one result, denoted as I (1), for all variables included in the estimation process.

To determine whether a true long-term link between the variables is present, the researchers use the Pedroni[65] panel co-integration analysis as well as the Bootstrapped panel co-integration analysis developed by Westerluns[66] (see Table 6). For doing panel co-integration tests, Pedroni[65] provides a thorough methodology similar to the two-step Engle and Granger approach.

This approach successfully handles panel heterogeneity by early removal of short-term characteristics and individual-specific deterministic patterns. Based on estimated residuals, Pedroni's method produces seven different test statistics that can be classified as either adopting a common procedure (called "pooled" or "within-dimension" tests) or a single procedure (named "grouped" or "between-dimension" analysis).

Using Westerluns's[66] technique, the authors add four more tests to Pedroni's approach, with the null hypothesis assuming no cointegration. In contrast to tests that rely on residuals, which could be limited by common elements, Westerluns' method emphasizes structural variation over residuals. This method removes the need for common factor assumptions by easing the requirement for similar long-term and short-term correction processes.

Moreover, this research endeavors to mitigate distortions arising from cross-sectional dependence by employing Westerluns's[66] bootstrap approach to derive robust critical values. A strong empirical foundation for the presence of a longstanding connection between the variables under investigation is established by the outcomes of the bootstrapped co-integration tests, which are reflected in Table 6 and offer convincing evidence for the presence of cointegration.[65,66]

Before conducting the variance inflation factor (VIF) test to discern any presence of multicollinearity or interrelation among the independent variables, this study initiated a linear regression analysis. The results of this analysis are reflected in Table 7. The absence of multi-collinearity is evident from the table, signifying the absence of any confounding regressions that could potentially distort conclusions. By a commonly accepted heuristic, multi-collinearity does not exist if the VIF is lower than the value 5. Table 7 corroborates this guideline, demonstrating no substantial correlations among variables such as aquaculture production, agriculture production, economic growth, fossil fuel consumption, and governance. Consequently, the VIF test assumes a pivotal role in safeguarding the validity and reliability of the regression analysis. Expanding on this, the linear regression analysis serves as a foundational step in uncovering potential relationships between the independent and dependent variables. By examining the coefficients and significance levels of each independent variable, researchers gain insights into their impact on the dependent variable. Subsequently, the VIF test provides a complementary assessment, probing the degree of correlation among the independent variables themselves. This step is essential to ensure that the regression results accurately reflect the true relationships within the data, devoid of any confounding influences stemming from multicollinearity. Furthermore, adherence to the VIF guideline helps to pre-emptively identify and mitigate any issues arising from multicollinearity, thereby fortifying the robustness of the regression analysis. By confirming the absence of significant correlations among the independent variables, Table 7 underscores the reliability of the regression findings and bolsters confidence in the validity of the study's conclusions.

ANALYZING THE ROBUSTNESS OF THE RESULTS

This study employs a multi-tiered approach to analysis, encompassing three distinct levels. Initially, the authors illuminate the interrelationships among various factors. Subsequently, they conduct an analysis integrating the aquaculture industry using the Ordinary Least Squares (OLS) regression technique. The ensuing results, presented

Table 6. Panel Cointegration Test in EU countries

Test	Without Trend	With Trend
A. Pedroni Residual Cointegration Test:		
Alternative hypothesis: common AR coefficients (within dimension):		
Panel v-Statistic	1.787 (0.963)	4.464 (0.992)
Panel rho-Statistic	1.181 (0.881)	2.117 (0.982)
Panel PP-Statistic	1.740*** (0.000)	1.019*** (0.000)
Panel ADF-Statistic	3.998*** (0.000)	6.217*** (0.000)
Alternative hypothesis: common AR coefficients (between dimensions)		
Group rho-Statistic	3.572	0.991
Group PP-Statistic	2.207***	(0.000)
Group ADF-Statistic	5.736***	(0.000)

Note: ***, ** and * refer importance at the 1%, 5%, and 10% scales respectively.
Values in parentheses are *p*-values.

Table 7. Variance Inflation Factor Estimation (VIF)

Variable	Coefficient	Prob.	VIF
AQ	0.060***	0.011	1.88
AG	0.159**	0.048	1.88
GDP	0.107*	0.075	1.43
GVR	0.038	0.213	1.41
FF	0.027	0.112	1.40
C	1.492***	0.000	

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels respectively.

below, are derived from the OLS regression, operating under the presumption that the aquaculture component is exogenous. Notably, the study identifies two explanatory variables, aquaculture and agriculture output, which may be interlinked and potentially lead to endogeneity issues. The researchers use Two-Stage Least Squares (2SLS) and Robust Least Squares (RLS) estimators to overcome this issue. Tables 8, 9, and 10 present the analysis's results for the precise study timeframe (1990–2023) as Table 10. Additionally, the economic development structure is stratified into industrialized and emerging member states in Tables 9 and 10, which correspond to the 2SLS and RLS regressions, accordingly.

The fundamental regression findings for Model 1 using the OLS, 2SLS, and RLS estimators for the EU27 region are shown in Table 8. Although the 2SLS and RLS results often support the OLS regression findings, the scales of the coefficients in the 2SLS or RLS regressions are frequently bigger. According to this, the third level of analysis uses 2SLS and RLS to evaluate the second level's results for robustness while keeping independent control variables constant. Agricultural output emerges as a consistent factor across all three parameters, both in terms of coefficient magnitude and statistical significance. An uptick in agricultural output manifests positive effects on food security, registering increments of 0.04%, 0.02%, and 0.06% respectively, as per the OLS estimate, 2SLS estimator, and RLS estimator in the EU27 region. In line with studies by Fujimori et al.,[26] Bazzana et al.,[27] and Verma et al.,[28] these findings highlight how various forms of agriculture, such as organic farming methods, can improve food security in the EU by 2030. These methods improve the quality of the soil, reduce greenhouse gases, and boost plant and animal life, all of which help create a more resilient and environmentally friendly food system.

Across all three estimation specifications (OLS, 2SLS, and RLS), it becomes apparent that aquaculture production exerts a significant positive impact on food security. In particular, for OLS, 2SLS, and RLS, accordingly, a 1% enhancement in aquaculture production has a favorable influence on food security of 0.02%, 0.01%, and 0.04% in the EU27 Region. Notably, the growth hypothesis is supported by considerable empirical data from both the 2SLS and RLS requirements, highlighting the outcomes' consistency across various estimate techniques and economic development contexts. These findings align with previous research supporting the main rule of the institutional economic theory. Aquaculture can increase food security in the EU by 2030 through Integrated Multi-Trophic Aquaculture (IMTA), an inventive method that combines the farm-

Table 8. Data Analysis for the European Union Member from 1990 to 2022

Factor	OLS		2SLS		RLS	
	Coeff.	Standard Err.	Coeff.		Coeff.	Standard Err.
AQ	0.022	0.074***	0.016	0.038***	0.048	0.020**
AG	0.044	0.023*	0.020	0.011*	0.159	0.066**
GDP	0.032	0.015**	0.014	0.090	0.049	0.042
FF	0.006	0.065	0.082	0.040**	0.026	0.018
GVR	0.010	0.059	0.037	0.032	0.024	0.016***
Constant	2.179	0.105***	2.006	0.052***	1.971	0.029***
R^2	0.031		0.013		0.057	
Adjusted-R^2	0.025		0.071		0.011	

Note: ***, ** and * indicate significance at the 1%, 5%, and 10% levels respectively.

ing of many species within the same ecosystem, in line with previous studies by Alsaleh[67] and Wang et al.[5,53] For example, fish farms can be combined with seaweed cultivation and shellfish production. This minimizes waste, improves water quality, and increases biodiversity, leading to a more sustainable and efficient system.

Furthermore, according to the 2SLS estimator, food security is boosted by a 0.08% rise in the percentage of fossil fuel consumption. This result is in line with earlier studies which show that fossil fuels contribute significantly to food security in the EU, mostly through transportation and machinery used in agriculture and aquaculture.[32,33,68] Fossil fuels power the machinery used in agriculture and aquaculture sectors, such as tractors, combines, and irrigation systems. They also fuel the transportation of agricultural and aquaculture products from farms to markets and processing facilities.

Table 9 reflects the outcome of the initial regression for Model 2 applying the OLS, 2SLS, and RLS regressors. Even though the coefficient magnitudes in the RLS and 2SLS regressions frequently seem greater, the results of these analyses support the OLS regression's findings. A statistically substantial and positive association between food security and maricultural is found in the EU14 members, as expected. The OLS, 2SLS, and RLS estimators, for example, produce food security gains of 0.01%, 0.01%, and 0.04% for every percentage increase in aquaculture production. This result supports earlier studies which show that aquaculture or fish farming can greatly increase food security in the EU14 by 2030 in some ways, such as giving priority to the sustainable intensification of current farms and investigating novel, cutting-edge production techniques like offshore aquaculture and recirculating aquaculture systems.[18,20,21]

Similarly, agricultural production emerges as the parameter exhibiting the highest degree of resilience from mathematical importance and co-efficient effect. Based on the OLS estimate, a 1.06% rise in agricultural output has a positive effect on food security, whereas the 2SLS and RLS estimation techniques reveal benefits of 0.07% and 0.12%, respectively, in the developed EU14 countries. This result corroborates studies by Pandey et al.,[30] Kumar and Sharma,[31] and Viana et al.,[29] advocating agroecology focuses on creating ecologically sound and socially just food systems that emphasizes biodiversity, closed-loop nutrient cycling, and the integration of livestock and crops.

Furthermore, of the three factors, economic growth (GDP) is the most robust concerning statistical importance and co-efficient size. The EU14 developed countries' OLS, 2SLS, and RLS estimators show that a 1% rise in economic growth has a positive impact on food security of 0.03%, 0.02%, and 0.02%, respectively. This result is consistent with studies by Kim et al. (2023), Aruna and Kumar (2023), and Sharma et al. (2023), which emphasize that economic expansion can stimulate investments in aquaculture and agricultural technology, resulting in higher yield and productivity. Food security may be strengthened as a result of improved food costs and availability.

Although its coefficient appears to vary depending on the specification, the most reliable element in all 3 regressors in terms of mathematical importance and co-efficient size is the fossil fuel input. For the OLS, 2SLS, and RLS regressors, the positive effects of a percentage increase in fossil fuel on food security are 0.06%, 0.05%, and 0.05%, respectively. This finding is in line with earlier papers that found high energy and raw material dependence on fossil fuels for the manufacturing of synthetic fertilizers, which are essential for contemporary agriculture and aquaculture.[34-36]

From a different angle, food security in the EU14 developed countries is improved by 0.04%, 0.06%, and 0.08% for the OLS, 2SLS, and RLS estimators, for example, for every percentage improvement in governance effectiveness. The institutional economic theory's support for nations that produce aquatic resources against the outcomes of Wang and Alsaleh,[54] who discovered that a whole-of-government approach and strong intermenstrual coordination are necessary to ensure that policies across various sectors (agriculture, aquaculture, livestock, etc.) are in line to support food security. Nonetheless, it is consistent with the principal findings of Ahwireng,[50] Iitembu et al.,[49] and Leeuwis et al.[48]

Table 10 reflects the standard analysis outcomes for Model 3, which includes OLS, 2SLS, and RLS regressors. Although the results of the OLS estimation are generally supported by the 2SLS and RLS results, the former usually show larger coefficient magnitudes. For the EU13 members,

Table 9. Data Analysis for the Developed European Union Member from 1990 to 2022

Factor	OLS		2SLS		RLS	
	Coeff.	Standard Err.	Coeff.	Std. Error	Coeff.	Standard Err.
AQ	0.017	0.075**	0.015	0.007***	0.047	0.053***
AG	1.065	0.028**	0.072	0.030**	0.120	0.046***
GDP	0.032	0.046***	0.024	0.040***	0.023	0.068***
FF	0.063	0.012***	0.053	0.012***	0.059	0.020***
GVR	0.049	0.016***	0.061	0.017***	0.085	0.023***
Constant	1.724	0.039***	1.744	0.038***	1.682	0.053***
R^2	0.164		0.162		0.076	
Adjusted-R^2	0.155		0.152		0.110	

Note: ***, ** and * indicate significance at the 1%, 5%, and 10% levels respectively.

aquaculture production is a significant and positive indicator of food security across all estimating parameters, including 2SLS, RLS, and OLS. Food security benefits from a percentage increase in aquaculture production are 0.05%, 0.03%, and 0.01% for OLS, 2SLS, and RLS, accordingly. As previously noted by earlier studies that emphasized how aquaculture can enhance the supply of farmed fish and lessen the strain on overfished wild stocks, ensuring the future viability of the marine environment to achieve food security.[19,22,23]

In a similar vein, food security is significantly and favorably impacted by agricultural productivity regardless of estimation criteria. In the EU13 developing nations, a percentage boost to agricultural output has beneficial effects on food security of 0.14%, 0.12%, and 0.08% for OLS, 2SLS, and RLS, respectively. These results are consistent with studies by Setsoafia et al.,[25] Fujimori et al.,[26] and Bazzana et al.,[27] which indicate that cultivating a range of crops lowers the chance of total crop failure brought on by pests, illnesses, or weather conditions, which has a favorable impact on the goals of food security.

Furthermore, the results for economic growth (GDP) under all three situations are comparable from the perceptive of computational importance and co-efficient size. For the EU13 developing countries, the OLS, 2SLS, and RLS estimators, respectively, show positive effects on food security of 0.03%, 0.03%, and 0.01% for every percentage rise in economic growth. Economic growth can affect trade patterns, which can affect domestic food security and international food supply, according to earlier studies.[40-42]

Additionally, while the coefficient for fossil fuel input varies with the specification, it shows promise across all three estimators. According to the OLS, 2SLS, and RLS regressors, the EU13 nations' food security benefits from a percentage rise in fossil fuels are 0.07%, 0.07%, and 0.06%, respectively. These results support prior research by Bhave et al.,[37] Shupler et al.,[38] and Rasul et al.,[39] highlighting the fossil fuels are used in the energy-intensive processes of food processing, such as refrigeration, canning, and packaging.

With a percentage gain in governance producing corresponding increases in food security of 0.07%, 0.09%, and 0.03% for the OLS, 2SLS, and RLS estimators, respectively, in the EU13 nations, good governance is a major driver of food security. This finding aligns with the intuitional economic concept, particularly applicable to countries producing aquatic resources. It echoes the primary findings of Collins,[46] Haysom,[52] and Anser[51] showing that building robust and diversified food systems can withstand shocks and stresses. This includes strengthening local and regional food systems, improving infrastructure, and enhancing food safety and quality controls.

DISCUSSION

The data's reliability and integrity are confirmed by the alignment of the values obtained from Panel 2SLS and RLS with those obtained from the OLS panel. The OLS coefficients' signs are consistent, despite the possibility that their significant thresholds deviate slightly from those of the panel 2SLS and RLS coefficients. The reliability of panel 2SLS estimates is further enhanced by the robustness of the estimates and the absence of endogeneity and serial correlation problems. To evaluate the effects of a burgeoning fish farming sector on food security, the EU27 region members were stratified into two categories: EU13 nations and EU14 wealthy nations, regarding the stages of their economic growth structure. The expected effects of the aquaculture and agriculture sectors on food security in EU14 nations are shown in Table 9, whereas Table 10 explores the contributions of these sectors to nutrition sufficiency in the EU13 members.

The findings shown in Tables 8 and 10 clearly show that sustainable food supply has been greatly enhanced by the expansion of the aquaculture sector. Furthermore, in EU13 countries, the influence of agricultural and aquaculture output on the sustainability of the food supply is noticeably greater than in EU14 countries. In the EU13 nations and EU14 developed nations, the respective amplitudes of these effects stand at 0.034 and 0.015 for aquaculture output, and 0.128 and 0.072 for agricultural production, respectively. This underscores that by fostering the fish farming industry in the EU13 developing nations, there is a greater potential to achieve food security aims by 2030.

Regarding economic growth, developing nations in the EU13 demonstrate a substantial and favorable influence

Table 10. Data Analysis for the Developing European Union Member from 1990 to 2022

Factors	OLS		2SLS		RLS	
	Coeff.	Standard Err.	Coeff.	Std. Error	Coeff.	Standard Err.
AQ	0.050	0.032***	0.034	0.032***	0.018	0.083***
AG	0.143	0.016***	0.128	0.016***	0.089	0.037***
GDP	0.036	0.040***	0.033	0.039***	0.010	0.010***
FF	0.076	0.076***	0.077	0.023***	0.064	0.069***
GVR	0.079	0.013***	0.094	0.015**	0.034	0.045***
Constant	2.022	0.033***	1.942	0.037***	1.938	0.010***
R^2	0.468		0.427		0.022	
Adjusted-R^2	0.461		0.419		0.037	

Note: ***, ** and * indicate significance at the 1%, 5%, and 10% levels respectively.

on food security compared to EU14 developed countries. Leveraging aquaculture and agricultural economics in the food supply chain could enable the EU13 developing countries to enhance food security at a faster pace. The countries in the EU13 and EU14 have specific influence magnitudes of 0.033 and 0.024, respectively.

Furthermore, the influence of government on food security is more detrimental in EU13 developing nations than in EU14 nations. The specific impact magnitudes for EU14 and EU13 countries are 0.061 and 0.094, respectively, suggesting that EU13 developing countries might improve food security by implementing blue governance and agricultural governance. Similarly, contrasted to the developed nations of the EU14, the utilization of fossil fuels has a more significant impact on food security in EU13 developing countries. The specific impact magnitudes for EU13 and EU14 countries are 0.077 and 0.053, respectively. These findings suggest that EU13 developing countries could expedite the enhancement of food security through the adoption of environmental policy and energy policy strategies. Overall, the results underscore that, in both EU13 members and EU14 members, agricultural output exerts a more substantial influence on food security than aquaculture production does. This highlights the critical importance of implementing sustainable development strategies and green agricultural policies to augment food security.

CONCLUSION AND IMPLICATIONS

This research explores the effects of aquaculture and agricultural sectors on food security, recognizing their potential contributions to economic and controller variables such as economic growth, fossil fuel use, and governance. Drawing from a panel data-set spanning the EU-27 nations from 1990 to 2023, the research employs OLS, 2SLS, and RLS regressors to explore these relationships. The outputs underscore the significant function of agriculture and fish farming in strengthening the sustainable stability of food supply, evident across all regression approaches. Notably, the study reveals disparities in the influence of agriculture and aquaculture on food security among EU14 members and EU13 members. It highlights the greater dependence of food security in EU13 countries on the agriculture sector and aquaculture sector. To achieve security, it emphasizes the critical need to bolster these sectors, along with promoting green development initiatives within EU13 developing countries.

Through empirical analysis, this study sheds light on the intricate dynamics between agriculture, aquaculture, and food security, providing valuable insights for policymakers and stakeholders striving to address food insecurity challenges.

The authors' findings reveal that EU13 economies surpass EU14 economies regarding food security goals achievement, attributed to governance, fossil fuel use, and GDP. To advance food security through aquaculture and agriculture, enhancing economic outgrowth, fossil fuel consumption, and governance techniques across various settings within the EU13 is crucial. The study underscores the pivotal function of the fish farming industry in encouraging blue farming sustainability to achieve food security, validated through robustness tests and additional analyses. From a fresh perspective, the study indicates that agriculture production contributes more significantly to food security aims than the fish farming industry in both EU13 developing countries and EU14 developed countries.

Strengthening agricultural productivity and sustainable development across these regions is essential for achieving better food security outcomes. Policymakers should prioritize measures to enhance the productivity of agriculture and aquaculture economies, particularly in EU14 developed countries with stagnant agricultural growth and inefficient aquaculture expansion. To sustain the growth of the aquaculture industry and marine environment for improved food security, policymakers in EU14 countries should focus on reducing fossil fuel usage and improving blue governance. Emphasizing green-blue farming methods, aquaculture productivity, efficiency, and governance is paramount for food security. Leveraging green technological advancements and digitalization can accelerate aquaculture ecosystem recovery and enhance sustainability. By establishing supportive regulations, developing ecological facilities, and fostering cooperation concerning aquaculture management and food security, authorities have the power to encourage the use of green technologies. Addressing these critical areas can create an enabling environment for the efficient expansion of the aquaculture industry and promote sustainable food security.

This research recommends the EU27 decision makers the following: (1) To address the key environmental challenges areas related to the agriculture sector that play a vital role in ensuring that people have access to sufficient, safe, and nutritious food. (2) Ensuring food security in the EU by 2030 will require a multi-faceted approach that addresses the complex challenges facing the food system. (4) Effective governance, based on strong policy coherence, innovation, and international cooperation, will be essential to achieve a sustainable, resilient, and equitable food system for all Europeans. (5) To embrace sustainable practices and address the marine environmental challenges, the aquaculture sector plays a vital role in ensuring global food security for generations to come. (6) Achieving economic growth while ensuring food security for all in the EU requires a multifaceted approach. By fostering sustainable agricultural and aquaculture practices, promoting responsible consumption, and addressing environmental challenges, the EU can create a food system that is both resilient and equitable. (7) Lastly, it's important to note that the EU is actively transitioning towards a more sustainable food system. This transition aims to reduce reliance on fossil fuels and mitigate their negative environmental impacts.

The study's focus on macroeconomic aspects of aquaculture and agriculture's impact on food security is not without limitation. Future research should explore more about microeconomic elements, including price, supply, and demand to provide a comprehensive understanding of food security at the country level based on the microeconomic level and national level of each country individually.

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